Operation of Electrostatic Photo-Multipliers

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(Received December 11, 1940)

This paper discusses the operation and characteristics of electrostatic photo-multipliers, using the Western Electric D-159076 photo-multiplier as an example to illustrate specific points. The following subjects are discussed: description of operation, advantages and applications, typical operating conditions, variation of sensitivity with voltage, hum due to ripple in power supply, effect of unequal voltage division, output impedance, linearity of response and fluctuation noises.

1.0 Introduction

Because of the newness of photo-multipliers, much which has been written concerning them has been of a general nature. One familiar with the field can obtain information concerning the electron emitting photo-cathodes,[1] the general theory of operation,[2] the problems of design and focusing[3, 4] and the evaluation of noise[4, 5] from various published writings. One who desires to utilize a photo-multiplier for the first time may find this material incomplete and confusing. For this reason the writers have endeavored to collect and present fairly complete information concerning the operation of photo-multipliers, including data on a typical commercial tube.

The tube chosen for the sake of illustration is the Western Electric D-159076 photo-multiplier. This tube consists of a caesium-oxygen-silver type photo-cathode in conjunction with a six-stage electrostatic type electron multiplier. The combination gives a highly light sensitive device, particularly sensitive in the red and infra-red, and therefore to light from incandescent sources.

2.0 Description of Operation

The photo-multiplier works in a circuit as shown in Fig. 1. The sensitized photo-cathode emits electrons at a rate proportional to the amount of light falling on it. The emitted electrons are attracted to the next more positive electrode in the series and strike it with an energy corresponding to the potential difference between the two electrodes. Part of this energy is utilized in the liberation of secondary electrons from the second electrode. The ratio of secondary electrons over incident electrons is the secondary emission ratio, or the current amplification per stage. The emission from the second electrode strikes the third where a similar amplification is produced, and so on through the series. If, for example, an average of 3.5 secondary elec-

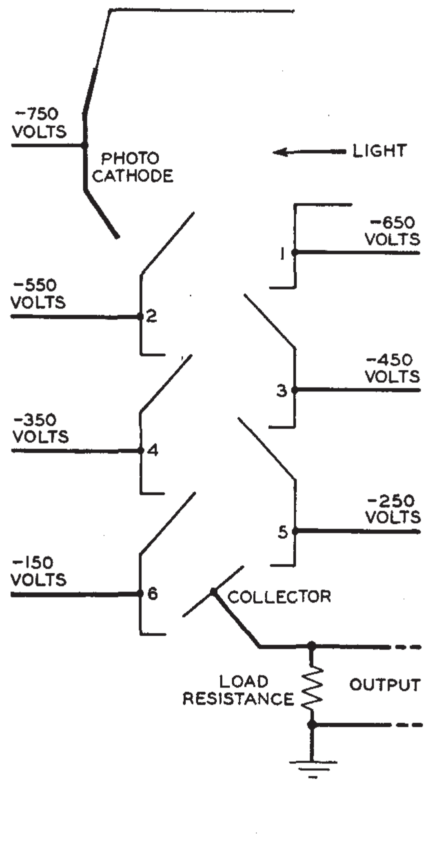

Fig. 1.

[1] C. H. Prescott, Jr., and M. J. Kelly, "Caesium-oxygen-silver photoelectric cell" Bell Sys. Tech. J. **11**, 334–367 (1932).
[2] V. K. Zworykin, G. A. Morton and L. Malter, "The secondary emission multiplier," Proc. I.R.E. **24**, 351–375 (1936).
[3] J. R. Pierce, "Electron multiplier design" Bell Lab. Rec. **16**, 305 (1938).
[4] V. K. Zworykin and J. A. Rajchman, "The electrostatic electron multiplier," Proc. I.R.E. **27**, 558 (1939).
[5] W. Shockley and J. R. Pierce, "A theory of noise for multipliers," Proc. I.R.E. **26**, 321–332 (1938).

trons are emitted for every primary electron striking each of the multiplier electrodes, and six multiplying stages are used, then the over-all current gain of the tube is $(3.5)^6$ or about 2000-fold. The cathode emission current amplified by that amount is delivered to the output electrode where it may be utilized in the same manner as the plate current of a regular vacuum tube. In effect, then, such a tube is the equivalent of a photo-cell plus a high gain d.c. amplifier.

In order to assure that the electrons follow the correct paths, guiding fields must be present. Some types of photo-multipliers must be mounted in suitable magnetic fields for this reason. These are generally referred to as magnetic type multipliers. In others, the electrostatic fields produced by the potentials on the multiplier plates are adequate to assure suitable electron paths, giving rise to the designation electrostatic type multipliers. The operation of these requires nothing further than the application of suitable potentials to the terminals of the tube. The D–159076 tube is of this latter class.

3.0 Advantages and Applications

The photo-multiplier is substantially equivalent to a vacuum photo-cell plus a high quality amplifier. The D–159076 photo-multiplier, for instance, has a gain of 70 db and is about 60 db more sensitive than the normal gas-filled photo-cell. The allowable voltage swing of the output is high enough to drive a power amplifier directly. These characteristics enable the multiplier to replace the photo-cell and preamplifier used in many applications with a resultant saving of space and equipment.

Other advantages of the photo-multiplier consist principally in frequency response and signal to noise ratio. As a comparison, the gas-filled photo-cell is suitable only for frequencies below ten kilocycles, while the photo-multiplier is good up to frequencies of several megacycles. The higher signal to noise ratio for the photo-multiplier extends its range of usefulness to much lower light intensities.

The photo-multiplier may well find applications in many fields where the advantages enumerated above are of practical importance. One such type of application lies in the conversion of modulated light to electrical signals. The frequency response and high sensitivity should also make the photo-multiplier useful in various types of television pick-up systems.

The high sensitivity characteristic and high output level make the photo-multiplier useful in various fields of light measurement. In the fields of spectrometry, colorimetry and photometry of faint sources the high sensitivity is especially valuable. The high output level, on the other hand, makes the photo-multiplier very useful in simple equipment for checking light sources and illumination level, and for smoke detection. Both characteristics are of value in light relay applications, such as counting, sorting, and illumination control. When used only for relay operations the photo-multiplier may be operated either on a d.c. or an a.c. voltage supply, acting as a self-rectifier in the latter case. The supply in this case may consist simply of a suitable tapped transformer. It is possible to operate a sensitive relay directly with the output current of the tube, thus eliminating amplifier or gas-filled tubes.

4.0 Typical Operating Conditions and Static Characteristics

In considering the use of the photo-multiplier, it is important to form some estimate of the required operating voltages, the currents available, etc. The following are the recommended operating conditions for the D–159076 tube: nominal total supply potential—750 volts; recommended potential per stage—100 volts; maximum recommended potential per stage—150 volts; approximate static sensitivity at 100 volts per stage to incandescent light source at a color temperature of 2710°K—40 milliamperes per lumen; maximum output current—2 milliamperes.

Photo-multipliers are high sensitivity devices designed to operate at low light flux. They should be guarded against even temporary exposure to strong illumination when voltages are applied to the electrodes.

4.1 Changes in sensitivity during operation

Photo-multipliers using Cs-O-Ag surfaces for the active surfaces are apt to go through certain changes in sensitivity during operation. When voltage is applied to the multiplier and light

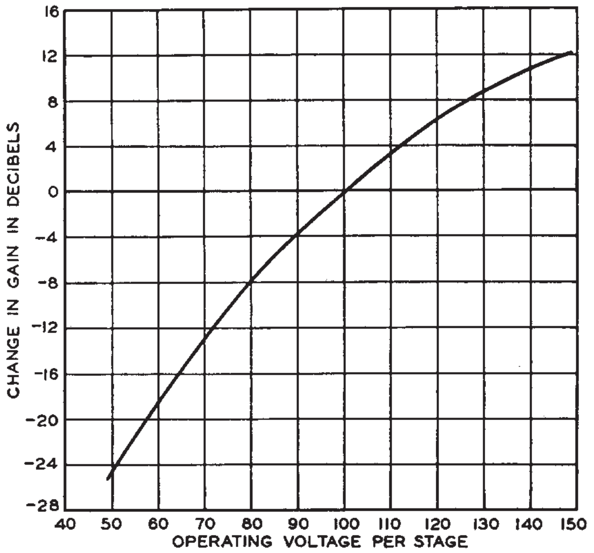

Fig. 2.

allowed to fall on the photo-cathode, an initial rise in sensitivity is observed. This rise usually approaches its final value in about 15 or 20 minutes. If the voltages and light are removed for a period of an hour or more, this initial rise will again occur approaching the same final value as before. On continued usage the drop in sensitivity while not in use tends to decrease and the time required to reach the final value also decreases.

In addition to this initial change, there is also a slow long-time increase in sensitivity. With continued use, the final value reached after the initial rise increases slightly. This increase is slow enough so that it will not interfere with the use of the multiplier in measuring equipment.

4.2 Variation of sensitivity with voltage

If it is desired either to increase or decrease the sensitivity of a photo-multiplier, this can be done by increasing or decreasing the operating voltage, because the secondary emission ratio of the surfaces is a function of voltage. In the case of the Cs-O-Ag surface the ratio has a peak value in the neighborhood of 400 v, and maximum sensitivity could be obtained by increasing the voltage per stage to this value. However, use of so high a voltage may result in damage to the multiplying surfaces, due to bombardment, breakdown of insulation, and excessive leakage currents. To insure the life of the tube, the voltage per stage should not exceed the maximum recommended value for the tube in question.

Figure 2 shows the manner in which the over-all sensitivity of the D–159076 photo-multiplier varies with the voltage per stage. The curve is a plot of the change in gain of the multiplier in db *versus* the operating voltage per stage, referred to the gain of the multiplier when operating at 100 volts per stage. For instance, if the multiplier is operated at 120 volts per stage instead of 100 volts per stage, the over-all gain will be 6 db above the gain at 100 volts. If the operating voltage is reduced to 80 volts per stage, the gain will be 8 db below the gain at 100 volts per stage.

4.3 Hum due to ripple in power supply

The variation of sensitivity of the multiplier with the operating voltage causes hum in the output when there is a ripple in the voltage supply to the tube. The hum level can be determined mathematically with the aid of a curve similar to that in Fig. 2. When this is done the following result is obtained,

$$\frac{\text{Hum}}{\text{Signal}}\,\text{db} = -K + 20\log_{10}\left(\frac{N}{N+1}\Delta V\right). \quad (1)$$

Here K is a constant determined by the slope of the gain *vs.* voltage characteristic of the multiplier, N is the number of stages of multiplication and ΔV is the ripple voltage in the over-all operating voltage supplied to the tube. The constant K can be determined for any particular tube if a curve like that of Fig. 2 is available for it. From this a plot of the slope (in db) of this curve against operating voltage at which the slope is taken is made. This is a plot of K in db *versus* the operating voltage, making it possible to determine K for any operating voltage.

Such a curve for the D-159076 tube is a straight line and can thus be incorporated in Eq. (1) with the following result:

$$\frac{\text{Hum}}{\text{Signal}}\,\text{db} = -(29.4 + 0.0163V) + 20\log_{10}\left(\frac{N}{N+1}\Delta V\right). \quad (2)$$

Here V is the over-all operating voltage, ΔV is the ripple voltage and N is the number of stages.

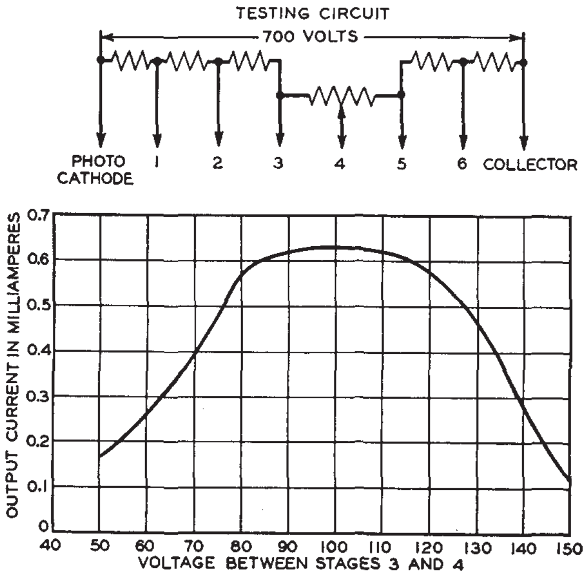

FIG. 3.

It will be noticed that (2) is independent of both the photo-cathode current and the output current. Thus the hum level will be constant for all illuminations unless the signal output current is of the same order of magnitude as the dark current.

Relation (2) makes it possible to determine the allowable ripple in the power supply to keep the hum level below a certain value. As an example consider a six-stage multiplier operating at 100 volts per stage or an over-all voltage of 700 volts. For the particular application, assume the desired hum level to be -40 db. To what value of ripple voltage must the power supply be regulated to be within this limit?

$$V=700 \text{ v}, \quad N=6, \quad \frac{\text{Hum}}{\text{Signal}} \text{ db} = -40 \text{ db}.$$

Substituting these values in (2)

$$-40 = -40.8 + 20 \log (6/7\Delta V)$$
$$\Delta V = 1.28 \text{ volts}.$$

This means that the filtering and regulation of the power supply must be such that the ripple voltage in the 700 volts does not exceed 1.28 volts if the hum is to be 40 db below the signal.

When working at low light levels, at which the signal current is of the same order of magnitude as the dark current, the hum level is raised. The amount of this increase can be expressed approximately by

$$20 \log_{10} (I_D + I_0)/I_0,$$

where I_D is the dark current and I_0 is the signal current without the dark current included. The hum to signal ratio then becomes

$$H' = H + 20 \log_{10} (I_D + I_0)/I_0,$$

where H is the hum level as calculated by Eq. (2) and H' is the hum level under the particular conditions of low light level.

4.4 Effect of unequal voltage division

In designing a voltage divider for the multiplier, the question arises as to how accurate the voltage division must be to insure the best results. To check this, measurements were made of the output current of the D-159076 multiplier with various voltages on the fourth stage while all other voltages remained fixed. The supply circuit to the tube for these measurements is indicated on Fig. 3. The resulting curve, also shown on Fig. 3, is a plot of the output current *versus* the voltage between the third and fourth stages. It will be noticed by looking at the circuit used that decreasing the voltage between stages 3 and 4 also increases the voltage between stages 4 and 5. If an operating voltage of 100 volts per stage is used, the curve shows that if the voltage on any stage is between 95 and 105 volts, there will be no noticeable difference in the output. On this basis, a variation of ± 5 percent appears to produce substantially no change in the sensitivity of the device. A divider of this accuracy should be easy to build as resistors of 2 percent tolerance are readily available. The current along the divider will vary because of the currents drawn by the various electrodes. If equal resistances are used in the divider, the divider current should be at least five times the output current to prevent the voltages on various stages from differing by more than 5 percent.

5.0 OUTPUT IMPEDANCE

When considering the multiplier for use with an amplifier or a high impedance circuit, it is well to know how the output current varies with the voltage of the collector. This is a measure of the output impedance of the tube. Figure 4 shows a plot for the D-159076 of the output current

versus the collector voltage (voltage with respect to the last multiplier stage) for two values of output current when operating at 100 volts per stage. The curves are flat and horizontal in the range from 75 v to 150 v, the current tending to drop off outside of this range. This means that the tube will deliver a peak voltage swing of 75 volts without distortion. When the multiplier is followed by an amplifier, the load impedance in the collector circuit of the multiplier should be so chosen that the collector voltage will always be within the range 75 v to 150 v. The operation of the multiplier will then be linear.

As an example of how this works, assume a multiplier having a sensitivity of 40 milliamperes per lumen at 100 v per stage operating under such conditions that the light varies from zero to 0.05 lumen. The collector current will range from zero to 2 milliamperes. Also assume that the full voltage swing of 75 volts is needed. The collector supply voltage, which will be the collector voltage at zero light and zero current, should be 150 volts. At full light and 2 milliamperes current the collector voltage should be 75 volts. This means that 2 milliamperes should give a drop of 75 volts in the load impedance, requiring a resistance of 37,500 ohms.

When the photo-multiplier is to be used for broad frequency bands, the output capacity must also be considered. This acts as a shunt capacity across the output impedance in the same manner as in a regular vacuum tube. The D-159076 photo-multiplier has an output capacity of 3.4 $\mu\mu$f, which at a frequency of 2 megacycles has an impedance of 23,500 ohms. This means then that if the response is to be held within 3 db up to 2 megacycles, the load resistance should not be greater than 23,500 ohms. The photo-multiplier even with this load resistance will still give a voltage swing of 33 volts at 2 megacycles if the full output of the tube is used.

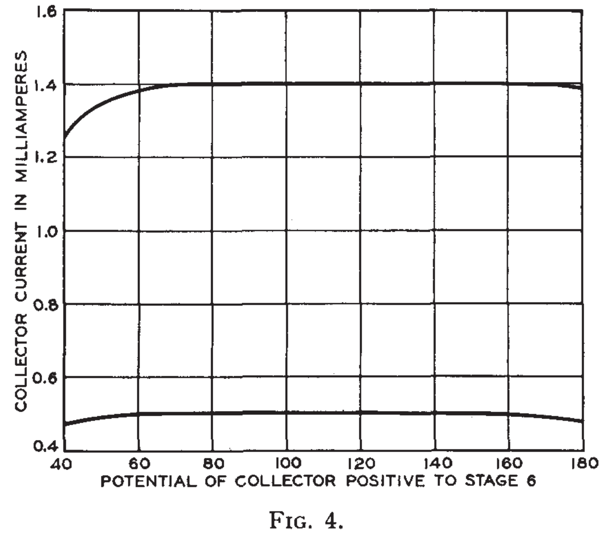

FIG. 4.

6.0 Linearity of Response

A photo-sensitive device for general use should have a linear response to light of varying intensity. That is, the output current should be proportional to the amount of light falling on the cathode. A vacuum photo-cell is known to have such a linear response. The secondary emission ratio of the multiplying surfaces is constant with current. This means that a photo-multiplier should have a linear response to light, providing space charge does not destroy the focusing action and thus ruin the linearity of response. Measurements on the D-159076 have indicated a linear response within the operating range to the accuracy of the measuring technique.

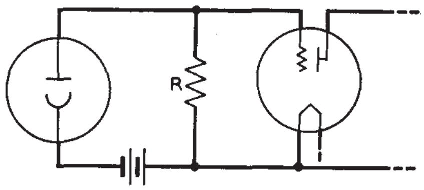

FIG. 5.

7.0 Fluctuation Noises in Photo-Cell Circuits and Multipliers

The purpose of this section is to evaluate and compare certain noises which are necessarily present in photo-cell circuits and in multipliers. These noises have already been treated in detail, and the present presentation is merely a simple compilation of material already presented elsewhere.[2, 5–7]

7.1 Photo-cell circuits

A simple photo-cell circuit is shown in Fig. 5, comprising a photo-cell and a load resistance R in

[6] H. Nyquist, "Thermal agitation of electric charge in conductors," Phys. Rev. **32**, 110–113 (1928).

[7] T. C. Fry, "The theory of the Schroteffekt," J. Frank. Inst. **199**, No. 2 (1925).

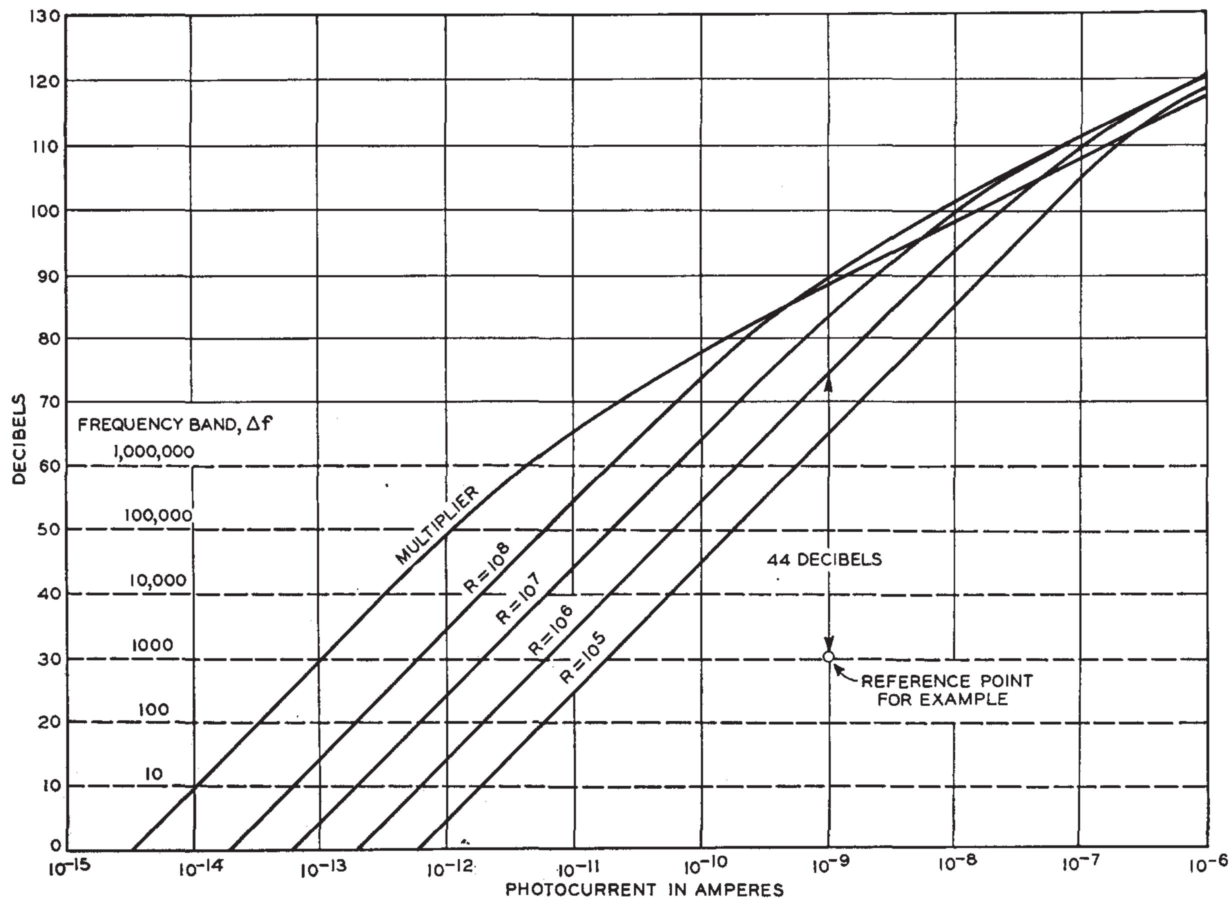

FIG. 6.

the grid circuit of the first tube of a vacuum tube amplifier. There are two sources of noise voltage across the resistor; thermal noise, and the IR drop due to shot noise in the photo-current I. Neglecting the input capacitance, the mean square thermal noise voltage across the resistor is[6]

$$\begin{aligned}\overline{E_t^2}&=4kTR\Delta f\\&=5.48\times10^{-23}\,TR\Delta f.\end{aligned}\qquad(3)$$

Here T is the absolute temperature of the resistance and Δf is the band width considered in cycles. Thus, if the amplifier following the photo-cell passes a band of 10,000 cycles, Δf will be 10,000.*

If $T=300°K$ (a reasonable room temperature)

$$\overline{E_t^2}=1.64\times10^{-20}\,R\Delta f.\qquad(4)$$

The shot noise current in the resistor may be expressed[7]

$$\begin{aligned}\overline{I_s^2}&=2eI\Delta f\\&=3.18\times10^{-8}\,I\Delta f,\end{aligned}\qquad(5)$$

where I is the mean photo-current. The mean square noise voltage will then be

$$\overline{E_s^2}=3.18\times10^{-19}\,R^2I\Delta f.\qquad(6)$$

The mean square sinusoidal signal current and voltage which can be obtained with a peak current I, are

$$\overline{I_0^2}=I^2/2,\qquad(7)$$

$$\overline{E_0^2}=R^2I^2/2.\qquad(8)$$

* If the output impedance of the photo-cell is appreciably reactive over the band width, R should be replaced in Eq. (4) by the resistive component of the impedance, and in Eq. (6) by the absolute value of the impedance. Subsequent equations also should be modified.

Thus the signal to noise ratio from (4), (6) and (8) is

$$\frac{\overline{E_0^2}}{\overline{E_n^2}}=\frac{\overline{E_0^2}}{\overline{E_s^2}+\overline{E_t^2}}$$

$$=\frac{1}{(6.36\times10^{-19}/I+3.28\times10^{-20}/RI^2)\Delta f}. \quad (9)$$

In db, the signal to noise ratio is

$$\frac{\text{Signal}}{\text{Noise}}\,\text{db}=-10\log\Delta f$$

$$-10\log(6.36\times10^{-19}/I+3.28\times10^{-20}/RI^2). \quad (10)$$

In Fig. 6 the signal to noise ratio in db is represented as a function of photo-current I in amperes for various values of resistance R in ohms. The signal to noise ratio is the difference between the height of the appropriate "R" curve and the horizontal line corresponding to the appropriate value of Δf, the band width in cycles.

As an example, consider a photo-cell with a photo-current of 10^{-9} ampere operating into an amplifier with a band width of 1000 cycles. The intersection of the vertical line marked 10^{-9} ampere with the horizontal line marked $\Delta f=1000$ gives a "reference point" marked with a circle on Fig. 6. Suppose the load resistance of the photo-cell is $R=10^6$ ohms. Then the distance between the reference point and the curve $R=10^6$, indicated in Fig. 6, gives the signal to noise in db, 44 db as read on the db scale to the right.

7.2 Noise in photo-multipliers

Figure 7 shows a multiplier coupled to the first tube of a vacuum tube amplifier.

The mean square multiplier noise current in the output due to a photo-current I leaving the first multiplier may be expressed[5]

$$\overline{I_s^2}=3.18\times10^{-19}\,I(1+B)M^2\Delta f. \quad (11)$$

Here M is the over-all multiplication of the multiplier and B is a quantity depending on the surfaces and operating conditions of the multiplier.‡

‡ B can be expressed in terms of the gain per stage, the number of stages, and a factor which cannot be calculated or directly evaluated by experiment (reference 5). For multistage multipliers it seems expedient to use the simple form given here.

The mean square noise voltage across the resistance R is then

$$\overline{E_s^2}=3.18\times10^{-19}\,R^2I(1+B)M^2\Delta f. \quad (12)$$

From unpublished measurements by F. W. Reynolds of these Laboratories it appears that $(1+B)$ usually lies between 1.5 and 3, and $(1+B)=2.5$ seems a conservative estimate.

In addition, there is shot noise current due to thermal emission from the photo-cathode and the early multiplier stages. If the output dark current due to a certain plate is I_{od}, the noise in the output due to this current is

$$\overline{E_{ds}^2}=3.18\times10^{-19}\,R^2(1+B)I_{od}M_d\Delta f. \quad (13)$$

Here M_d is the total multiplication following the plate in question.

The thermal noise across the output resistance R is

$$\overline{E_t^2}=1.64\times10^{-20}\,R\Delta f. \quad (14)$$

The maximum possible mean square sinusoidal voltage which can be achieved by modulating the photo-current I is

$$\overline{E_0^2}=M^2R^2I^2/2. \quad (15)$$

The signal to noise in db is then

$$\frac{\text{Signal}}{\text{Noise}}\,\text{db}=-10\log\Delta f$$

$$-10\log\left(\frac{6.36\times10^{-19}(1+B)}{I}+\frac{3.28\times10^{-20}}{RM^2I^2}+\sum_d\frac{6.36\times10^{-10}\,(1+B)}{M^2I^2}M_dI_{od}\right). \quad (16)$$

In general, the term involving R is quite small, and is negligible for values or $R>10{,}000$ ohms. Figure 6 gives signal to noise ratio for photo-multipliers for the following parameters, which are average values for the D-159076 multiplier $(1+B)=2.5$, $R=10{,}000$ ohms, $M=4000$; $I_{od1}=0.025$ μa, $M_{od1}=4000$; $I_{od2}=0.010$ μa, $M_{od2}=1000$; $I_{od3}=0.016$ μa, $M_{od3}=250$. The value I_{od1} is the output dark current due to thermal emission from the photo-cathode, I_{od2} that due to thermal emission from the first stage, etc.; M_{od1} is the multiplication undergone in producing I_{od1}, etc.

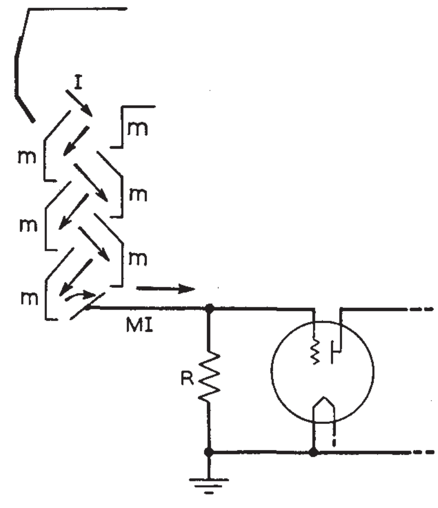

FIG. 7.

The three dark currents listed are the only ones which contribute significantly to the summation term in (16). Putting the above values in (16) gives for the signal to noise ratio

$$\frac{\text{Signal}}{\text{Noise}}\,\text{db} = -10\log \Delta f$$
$$-10\log\left(1.59\times10^{-18}/I + 1.15\times10^{-29}/I^2\right). \quad (17)$$

It is from this expression that the multiplier curve in Fig. 6 was plotted. It may be seen that at low levels the multiplier noise is due largely to dark current and may be reduced by cooling the multiplier.

7.3 Effect of stray light on noise level

In calculating the signal to noise ratio, it has been assumed that all the light falling on the photo-cathode and giving rise to photo-current can be considered as signal. If stray light falls on the photo-cathode the signal to noise ratio will be lowered, even if the stray light is perfectly steady.

Suppose the total photo-current leaving the photo-cathode is

$$I = I_0 + I_n, \quad (18)$$

where I_0 is the signal current and I_n is the current due to stray light.

Counting I as the total photo-current, we can find the "signal to noise" ratio from the diagram. This is the signal to noise ratio corresponding to complete modulation of the current I, while completely modulating signal current I_0 will only modulate the current I a fraction I_0/I. Thus, if N is the signal to noise ratio in db for a completely modulated photo-current I, the actual attainable signal to noise ratio for a completely modulated signal current, I_0, will be

$$N' = N - 20\log\frac{I_0}{I}\,\text{db}. \quad (19)$$

7.4 Keeping the noise level low

From the point of view of noise, the multiplier is superior to the photo-cell-amplifier combination whenever the multiplier curve in Fig. 6 lies above the highest usable photo-cell curve. Thus the multiplier is always superior for very small light inputs. It is especially advantageous for wide band usage, when the load impedance of a photo-cell must be made small. From Fig. 6 it can be seen that in the case of a photo-cell, the lower the load resistance, the less favorable the signal to noise ratio. In the case of the multiplier, a load resistance of 10,000 ohms has been assumed. This contributes a negligible noise, and yet is much lower than could be used with a photo-cell. If the voltage is available, it is generally desirable to use as much multiplication

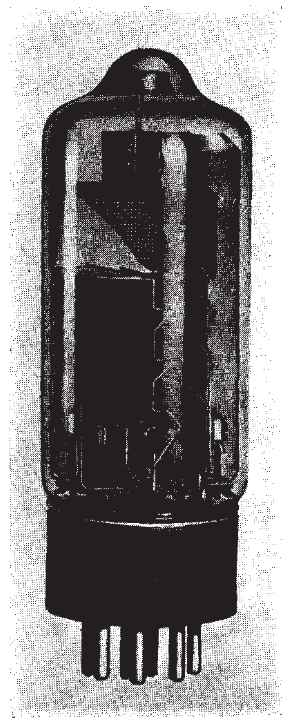

FIG. 8.

as possible without overloading the multiplier, in order to get a large signal.

In avoiding trouble from noise it is important to use as narrow a band width as possible. Thus, in devices used merely to obtain meter readings corresponding to a light input at a fixed frequency, it is desirable to use amplifiers in which several sharply tuned filters are incorporated.

It is also important to avoid stray light, which adds to the noise without increasing the signal.

In the absence of stray light the signal to noise ratio can be improved by cooling the multiplier with dry ice and thus reducing dark current. If stray light gives a zero signal current larger than the thermionic dark current, cooling the multiplier is futile.

Figure 8 is a photograph of a Western Electric D-159076 photo-multiplier, the tube used as an example in this paper.